

Combined CDF and D0 upper limits on Fermiophobic Higgs Boson Production with up to 8.2 fb^{-1} of $p\bar{p}$ data

The TEVNPH Working Group*

for the CDF and D0 Collaborations

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We combine the results of searches by the CDF and D0 collaborations for a fermiophobic Higgs boson (H_f) produced via the processes WH_f , ZH_f , and vector-boson fusion in $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ at the Fermilab Tevatron collider. The analyses seek Higgs boson decays to W^+W^- and $\gamma\gamma$. With up to 8.2 fb^{-1} of integrated luminosity analyzed at CDF and up to 8.2 fb^{-1} at D0, we obtain a 95% CL lower bound on the mass of the Higgs boson in the fermiophobic Higgs model of $119 \text{ GeV}/c^2$.

Preliminary Results

* The Tevatron New-Phenomena and Higgs Working Group can be contacted at TEVNPHWG@fnal.gov. More information can be found at <http://tevnphwg.fnal.gov/>.

I. INTRODUCTION

The mechanism for the breaking of the $SU(2) \times U(1)$ electroweak gauge symmetry [1] of the standard model (SM) [2] has thus far evaded experimental verification even though the SM accommodates current collider data and it has been tested with remarkable precision. Searches for the SM Higgs boson at LEP [3], the Tevatron [4], and the LHC [5, 6] have yet to confirm its existence.

The mechanism of electroweak symmetry breaking may offer a richer phenomenology than expected in the minimal version of the SM. Several Higgs bosons may exist, or the Higgs boson(s) may have couplings that are different from those expected in the minimal model. Here we explore the possibility that the lightest Higgs scalar does not couple to fermions at tree level, but is in all other ways SM-like. In order to provide masses to the fermions, additional degrees of freedom must exist in the Higgs sector, and models with Higgs doublets and triplets are possible [7–9]. We consider here a model in which all particles and interactions beyond those of the SM have no phenomenological impact for observables at the Tevatron aside from suppressing the fermion couplings to the Higgs boson. We call this model the fermiophobic Higgs model (FHM). In the following, we denote the fermiophobic Higgs boson H_f , the SM Higgs boson H_{SM} , and use the symbol H in a context which is valid for both.

In the FHM, the production of Higgs bosons at hadron colliders via the process $gg \rightarrow H_f$ is suppressed to a negligible rate. In the SM, this process proceeds through one-loop intermediaries via fermion couplings to the Higgs boson, and at two or more loops via fermion and boson couplings to the Higgs boson. Two-loop electroweak processes contribute to $gg \rightarrow H_f$ production in the fermiophobic Higgs model (FHM), but at a vanishingly small rate, as their main contribution in the SM are through interference with one-loop processes [10]. The associated production mechanisms $p\bar{p} \rightarrow WH_f + X$ and $p\bar{p} \rightarrow ZH_f + X$, as well as the vector-boson-fusion (VBF) processes $q'\bar{q} \rightarrow H_f q''\bar{q}'''$ remain nearly unchanged relative to the corresponding processes in the SM. Table I lists the production rates we use for the WH_f , ZH_f , and VBF modes. We neglect the cross section for $gg \rightarrow H_f$ in this model. We use the WH_{SM} and ZH_{SM} cross sections from Ref. [11], which are based on the next-to-leading-order (NLO) calculation of v2HV [12] and include next-to-next-to-leading-order (NNLO) QCD contributions [13], as well as one-loop electroweak corrections [14]. We use the VBF cross section computed in the SM at NNLO in QCD in Ref. [15]. Electroweak corrections to the VBF production cross section are computed with the HAWK program [16], and are small and negative (2-3%) in the Higgs boson mass range considered here. We include these corrections in the VBF cross sections used in this combination of results from the Tevatron. We use the systematic uncertainties on the production cross section predictions from their respective publications, treating the WH_f and ZH_f production cross section uncertainties as fully correlated with each other, and uncorrelated with the VBF production cross section uncertainty.

Another consequence of the FHM is to modify the decay branching ratios of the Higgs boson with respect to the SM predictions. Direct decays to fermions are forbidden; decays to fermions can proceed only via loops involving weak gauge bosons, and these are highly suppressed due to a spin flip required in the loop. The partial width of the Higgs boson decay to a pair of gluons, which in the SM is comparable to that of the decay to a pair of charm quarks, is negligibly small in the FHM. The remaining decays, to $\gamma\gamma$, W^+W^- , $Z\gamma$, and ZZ , account for nearly the entire decay width. For Higgs boson masses below twice the W boson mass, $m_{H_f} \ll 2M_W$, the favored direct decay to W^+W^- is reduced because one or both of the W bosons is far from resonance. Nonetheless, because the competing decay modes have small partial widths, the branching to W^+W^- is still dominant, particularly for a heavier Higgs boson with $m_{H_f} > 120 \text{ GeV}/c^2$. The branching fraction $\mathcal{B}(H_f \rightarrow \gamma\gamma)$ is greatly enhanced over $\mathcal{B}(H_{\text{SM}} \rightarrow \gamma\gamma)$ for all m_H , and its clean signature and excellent mass resolution provide most of the search sensitivity for $m_{H_f} < 120 \text{ GeV}/c^2$.

Table I lists the decay branching fractions we assume in the searches described below, all of which were computed with HDECAY [17]. The dominant uncertainties on the SM Higgs branching fractions in the range $100 \text{ GeV}/c^2 < m_{H_{\text{SM}}} < 200 \text{ GeV}/c^2$ arise from uncertainties on the b quark mass m_b , the charm quark mass m_c , and the strong coupling constant α_s [18, 19]. Because these uncertainties affect only the decay modes in which a fermion (specifically, a quark) couples to the Higgs boson, they do not affect the Higgs boson's branching ratios in the FHM, and therefore they do not contribute to this analysis.

The CDF and D0 collaborations have searched for the SM Higgs boson in $H_{\text{SM}} \rightarrow \gamma\gamma$ decays [20, 22]. These searches cannot be directly reinterpreted as constraints on the FHM by simply scaling the cross sections and branching ratios, because the kinematic distributions of the Higgs bosons, their decay products, and the particles produced in association with the Higgs boson differ between the FHM and the SM. These differences arise from the absence of

TABLE I: The production cross sections for WH_f , ZH_f , and VBF at NNLO. Also listed are decay branching fractions (\mathcal{B}) of the Higgs boson in the Fermiophobic Higgs model computed with HDECAY [17].

m_{H_f} (GeV/ c^2)	σ_{WH} (fb)	σ_{ZH} (fb)	σ_{VBF} (fb)	$\mathcal{B}(H_f \rightarrow \gamma\gamma)$	$\mathcal{B}(H_f \rightarrow W^+W^-)$	$\mathcal{B}(H_f \rightarrow ZZ)$
100	291.9	169.8	97.2	0.185	0.735	0.0762
105	248.4	145.9	89.7	0.104	0.816	0.0733
110	212.0	125.7	82.7	0.0603	0.853	0.0788
115	174.5	103.9	76.4	0.0366	0.866	0.0887
120	150.1	90.2	70.7	0.0233	0.869	0.0993
125	129.5	78.5	65.3	0.0156	0.868	0.109
130	112.0	68.5	60.4	0.0107	0.867	0.116
135	97.2	60.0	55.9	0.759×10^{-2}	0.866	0.120
140	84.6	52.7	51.8	0.544×10^{-2}	0.868	0.121
145	73.7	46.3	48.1	0.390×10^{-2}	0.874	0.118
150	64.4	40.8	44.6	0.273×10^{-2}	0.886	0.108
155	56.2	35.9	41.2	0.176×10^{-2}	0.909	0.0871
160	48.5	31.4	38.2	0.835×10^{-3}	0.951	0.0466
165	43.6	28.4	36.0	0.334×10^{-3}	0.975	0.0236
170	38.5	25.3	33.4	0.226×10^{-3}	0.975	0.0246
175	34.0	22.5	31.0	0.179×10^{-3}	0.966	0.0332
180	30.1	20.0	28.8	0.148×10^{-3}	0.939	0.0609
185	26.9	17.9	26.9	0.118×10^{-3}	0.848	0.152
190	24.0	16.1	25.0	0.979×10^{-4}	0.788	0.212
195	21.4	14.4	23.3	0.852×10^{-4}	0.759	0.241
200	19.1	13.0	21.6	0.759×10^{-4}	0.742	0.258

$gg \rightarrow H_f$ production in the FHM, and the increased fraction of the presence of an associated vector boson W or Z , or recoiling quark jets in the case of VBF. The transverse momentum (p_T) spectrum of the Higgs boson in the FHM is thus much harder than it is in the SM, affecting the signal acceptance and the ability to separate the signal from the backgrounds. The $H_f \rightarrow \gamma\gamma$ analyses have therefore been reoptimized for the FHM, taking advantage of the higher p_T of the Higgs boson [21, 22]. These analyses are updates of previous searches for the Higgs boson in the FHM using 3.0 fb^{-1} of data at CDF [23] and 2.7 fb^{-1} of data at D0 [24]. The CMS collaboration has also sought Higgs bosons decaying to photon pairs, and sets a lower limit on m_{H_f} in the FHM of $112 \text{ GeV}/c^2$ at the 95% CL [25]. ATLAS has sought the SM Higgs boson in the decay $H_{\text{SM}} \rightarrow \gamma\gamma$ in 1.1 fb^{-1} of data [5]. The four LEP collaborations, ALEPH, DELPHI, L3, and OPAL, have searched for $e^+e^- \rightarrow ZH_f \rightarrow Z\gamma\gamma$, and from their combined results report a lower limit on m_{H_f} of $108.2 \text{ GeV}/c^2$ in the FHM at the 95% CL [26].

In addition to the searches for $H_f \rightarrow \gamma\gamma$, we also combine CDF's and D0's searches for $H \rightarrow W^+W^-$, taking advantage of its enhanced branching fraction in the FHM. As for $H \rightarrow \gamma\gamma$, the searches for $H_{\text{SM}} \rightarrow W^+W^-$ cannot be interpreted directly in the FHM due to the different mixture of production modes.

The CDF collaboration's $H_{\text{SM}} \rightarrow W^+W^-$ analyses [27] keep separate account of the predictions from $gg \rightarrow H_{\text{SM}}$, WH_{SM} , ZH_{SM} , and VBF in each of the contributing channels. The distributions of the neural-network discriminants of these analyses are reinterpreted in the FHM by setting the $gg \rightarrow H_f$ component to zero and by scaling the remaining signal components by the ratio of branching ratio predictions $\mathcal{B}(H_f \rightarrow W^+W^-)/\mathcal{B}(H_{\text{SM}} \rightarrow W^+W^-)$. CDF's searches for opposite-charge dilepton events in the final state $H_{\text{SM}} \rightarrow W^+W^- \rightarrow \ell^+\nu_\ell\ell'^-\bar{\nu}_{\ell'}$ (where $\ell, \ell' = e, \mu$), are separated into categories based on the number of reconstructed jets accompanying the leptons and missing transverse energy in the event. The $gg \rightarrow H$ process, which contributes negligibly in the FHM, most frequently produces a Higgs boson without additional jets, while the WH , ZH , and VBF production modes more commonly produce Higgs bosons with additional jets. This division of events into jet categories optimizes the search in the FHM and does not require developing a separate set of analysis channels, unlike the case of $H_f \rightarrow \gamma\gamma$. The opposite-charge low- $m_{\ell\ell}$ channel and the channels seeking $H \rightarrow W^+W^-$, in which one W decays into a τ lepton which then decays to hadrons+ ν_τ , while the other W decays to $e\nu$ or $\mu\nu$, are included in the combination. The trilepton and like-charge dilepton analyses,

TABLE II: Luminosity, explored mass range and references for the different processes and final states ($\ell = e$ or μ) for the CDF analyses. The label “2 \times ” refers to a separation based on lepton categories.

Channel	Luminosity (fb $^{-1}$)	m_{H_f} range (GeV/ c^2)	Reference
CDF $H_f \rightarrow \gamma\gamma$	7.0	100-150	[21]
CDF $H \rightarrow W^+W^-$ 2 \times (0 jets,1 jet)+(2 or more jets)+(low- $m_{\ell\ell}$)+(e- τ_{had})+(μ - τ_{had})	8.2	110-200	[27]
CDF $WH \rightarrow WW^+W^-$ (same-sign leptons)+(tri-leptons)	8.2	110-200	[27]
CDF $ZH \rightarrow ZW^+W^-$ (tri-leptons with 1 jet)+(tri-leptons with 2 or more jets)	8.2	110-200	[27]
D0 $H_f \rightarrow \gamma\gamma$	8.2	100-150	[22]
D0 $VH \rightarrow \ell^\pm\ell^\pm + X$	5.3	115-200	[28]

also included in CDF’s SM $H \rightarrow W^+W^-$ search [27], are included here as well, as they are targeted at the WH and ZH signal contributions.

The D0 SM searches for $H_{\text{SM}} \rightarrow W^+W^-$ included here are the like-charge dilepton searches [28], targeting the WH and ZH production modes, in which the W or Z produced in association with the Higgs boson decays leptonically and forms a like-charge pair with a lepton from one of the W decays. They are reinterpreted here as searches in the FHM by scaling by the ratio of branching ratios in the SM and FHM. CDF uses neural-network discriminants and D0 uses boosted decision trees as the final step in separating a possible signal from the backgrounds. The same multivariate discriminant functions used in the SM searches are used here without reoptimization for the FHM. A summary of the included channels and their luminosities is provided in Table II.

We use the same statistical methods employed in Ref. [29], namely the modified frequentist (CL_s) and Bayesian techniques, in order to evaluate the results. Pseudo-experiments drawn from the background predictions varied according to their systematic uncertainties are used to compute the limits we expect to obtain in the absence of signal. Correlated systematic uncertainties are treated in the same way as they are in Ref. [29]. The sources of correlated uncertainty between CDF and D0 are the total inelastic $p\bar{p}$ cross section used in the luminosity measurement, the SM diboson background production cross sections (WW , WZ , and ZZ), and the $t\bar{t}$ and single top quark production cross sections. Instrumental effects such as trigger efficiencies, photon and lepton identification efficiencies and misidentification rates, and the jet energy scales used by CDF and D0 remain uncorrelated. To minimize the degrading effects of systematics on the sensitivity of the search, the signal and background contributions are fit to data by maximizing a likelihood function over the systematic uncertainties for both the background-only and signal+background hypotheses [30]. We include the theoretical uncertainties on the predictions of the production cross sections when quoting limits normalized to them and when quoting our limit on m_{H_f} in the FHM.

The combined limits on Higgs boson production normalized to predictions of the FHM are listed in Table III for both the CL_s and the Bayesian methods, for $100 \text{ GeV}/c^2 < m_{H_f} < 200 \text{ GeV}/c^2$, in $5 \text{ GeV}/c^2$ steps. The expected and observed limits for both methods agree within 5% for nearly all m_{H_f} values except for $m_{H_f} > 185 \text{ GeV}/c^2$, where the agreement still remains close for the expected limit and is within 10% for the observed limits. We choose to present the limits calculated with the Bayesian approach which was selected *a priori*. The final limits are shown in Fig. 1. To quote a limit on m_{H_f} in the FHM, we interpolate the limits linearly between the sampled values of m_{H_f} and report the locations at which the observed and expected limit functions cross unity. We exclude $m_{H_f} < 119 \text{ GeV}/c^2$ at the 95% CL, and the expected exclusion range is also $m_{H_f} < 119 \text{ GeV}/c^2$.

In summary, we present a combination of CDF and D0 searches for the Higgs boson in a model in which the tree-level couplings of the Higgs boson to fermions vanish, while retaining standard model couplings to bosons. We exclude, at the 95% CL, a Higgs boson of mass $m_{H_f} < 119 \text{ GeV}/c^2$ in this model. This is the most restrictive limit to date on the fermiophobic Higgs model.

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TABLE III: Observed and expected limits from the combined Tevatron search for Higgs boson production in the fermiophobic Higgs model (FHM)

m_{H_f} (GeV/ c^2)	Bayesian		CL _s	
	obs (Limit/FHM)	Median exp (Limit/FHM)	obs (Limit/FHM)	Median exp (Limit/FHM)
100	0.16	0.17	0.17	0.17
105	0.44	0.31	0.44	0.31
110	0.36	0.52	0.38	0.52
115	0.72	0.81	0.75	0.81
120	1.07	1.05	1.06	1.03
125	1.23	1.27	1.20	1.22
130	1.45	1.44	1.47	1.41
135	1.26	1.55	1.29	1.51
140	1.44	1.77	1.47	1.69
145	1.83	1.78	1.80	1.75
150	1.90	1.88	1.87	1.83
155	1.83	1.90	1.80	1.95
160	1.83	1.84	1.78	1.86
165	1.43	1.87	1.46	1.85
170	1.64	2.11	1.66	2.09
175	2.17	2.32	2.11	2.36
180	2.57	2.75	2.51	2.73
185	3.85	3.39	3.66	3.34
190	4.97	3.89	4.48	3.90
195	5.36	4.20	4.90	4.36
200	5.96	4.80	5.34	4.85

(France), BMBF and DFG (Germany), Ministry of Education, Culture, Sports, Science and Technology (Japan), World Class University Program, National Research Foundation (Korea), KRF and KOSEF (Korea), DAE and DST (India), SFI (Ireland), INFN (Italy), CONACyT (Mexico), NSC(Republic of China), FASI, Rosatom and RFBR (Russia), Slovak R&D Agency (Slovakia), Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010 (Spain), The Swedish Research Council (Sweden), Swiss National Science Foundation (Switzerland), FOM (The Netherlands), STFC and the Royal Society (UK), and the A.P. Sloan Foundation (USA).

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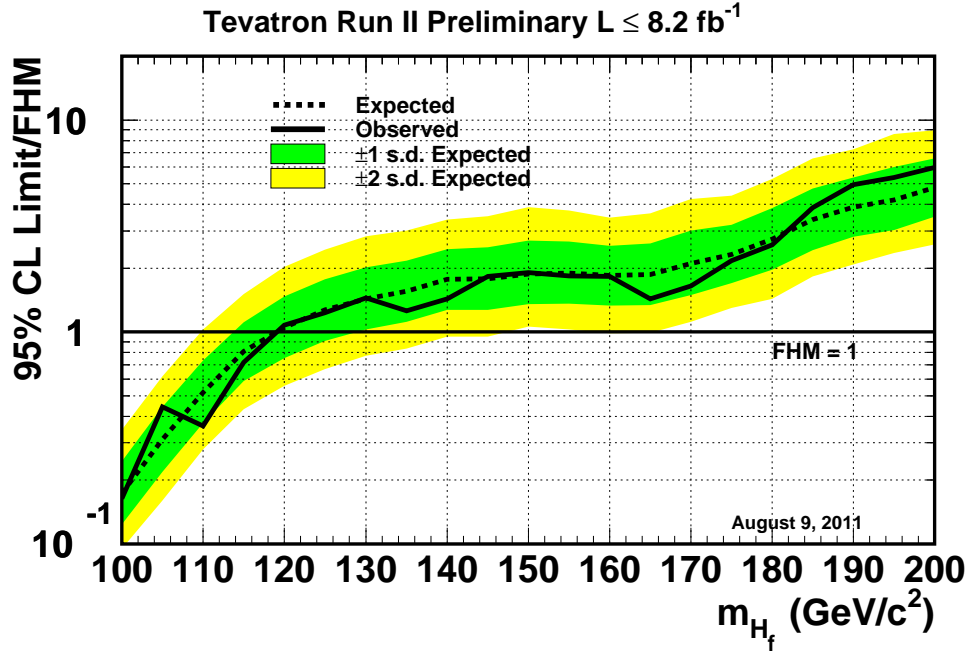


FIG. 1: Observed (solid black line) and median expected (dashed black line) 95% CL upper limits from the Tevatron on Higgs boson production in the fermiophobic Higgs model (FHM). The shaded bands indicate the ± 1 standard deviation (s.d.) and ± 2 s.d. intervals on the distribution of the limits that are expected in the absence of a contribution from the Higgs boson.

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